Recovering Value from End of Use Products: Reuse, Remanufacturing, and Recycling

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Sutherland Background

♦ Academic background: Manufacturing
♦ Pioneered the field of green manufacturing in the 1990s
  • Avoid waste → increase profit
  • Close material loops
  • Effective use of resources
  • Improve competitiveness by avoiding environmental problems
♦ Collaborated with Ford, GM, Caterpillar, Boston Scientific, Allied Signal, General Dynamics, Cummins, etc.
Learning Objectives:

♦ Focus is on discrete products
♦ Review options for product end-of-life
  • Life extension
  • Remanufacturing
  • Recycling
♦ Emphasize role of engineering design
♦ Environmental engineers have an important role to play in all of this!
Traditional View of Product Life Cycle

How long can we tolerate a situation:
- where waste is designed in?
- where used products are discarded?
- where processing/manufacturing wastes are “part of doing business”?
Closing Material Loops

New technologies to help close material/value loops

New business models that support this approach
Discrete Product Waste Hierarchy

Avoid, Reduce, Reuse, Remanufacture, Recycle, Recover, Energy, Dispose

Effectiveness, Design

Most preferred: Avoid, Reduce, Reuse, Remanufacture, Recycle, Recover, Energy, Dispose

Least preferred: Avoid, Reduce, Reuse, Remanufacture, Recycle, Recover, Energy, Dispose
Circular Economy Philosophy:
Products, components, and materials kept at highest utility and value at all times

Benefits:
- Reduced supply risk
- Improved environmental outcomes
- Improved profit

Adapted from http://ecm2016.com/circular-economy/
Product Life Extension

♦ Premature failure: product replacement
  • Increases environmental footprint
  • Economic and reputation impacts
♦ Extend product life with intelligent/smart maintenance
♦ WHIN – seeks to create hub for smart manufacturing
Remanufacturing vs. Recycling

♦ Remanufacturing preserves much of the functional value in a product – recycling only recovers material value

♦ Both close material loops – recycling does not recover energy/water/value invested thru original manufacturing

♦ Easier to remanufacture and recycle if products are designed with these end-of-use options in mind (Design for X)
Remanufacturing – Diesel Engine

- Profitable: less material and manufacturing costs
- Reduce waste and minimize the need for virgin material for new products
- Enabled by the relatively modest changes across product generations

**Typical engine remanufacturing process**

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Manufacture</th>
<th>Reman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine block</td>
<td>Cast iron</td>
<td>9970</td>
<td>600</td>
</tr>
<tr>
<td>Cylinder head</td>
<td>Cast iron</td>
<td>4445</td>
<td>1110</td>
</tr>
<tr>
<td>Crankshaft</td>
<td>Steel</td>
<td>2800</td>
<td>110</td>
</tr>
<tr>
<td>6 Connecting rods</td>
<td>Steel</td>
<td>330</td>
<td>10</td>
</tr>
<tr>
<td>6 Pistons</td>
<td>Steel</td>
<td>555</td>
<td>20</td>
</tr>
<tr>
<td><strong>Total energy required (MJ)</strong></td>
<td><strong>18100</strong></td>
<td><strong>1850</strong></td>
<td><strong>16250</strong></td>
</tr>
<tr>
<td><strong>Avoided energy with reman (MJ)</strong></td>
<td><strong>16250</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

16,250 MJ (4,513 kWh) represents $325.84 in energy cost savings*

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* Caterpillar, mid 2000s
Explosive Growth in Electric Vehicles

- Tesla, GM, Volkswagen, Ford, etc. all investing heavily in EVs
- Key components:
  - Electric Motors
    - Magnets - Nd(Dy)FeB
  - Batteries – Li, Co
- Nd and Dy are critical, rare earth elements (REEs)
- Li & Co are also critical matls.
- “Critical materials” have no substitutes (without performance loss), have high supply risk, and are essential for many clean energy appls.

Applications of Critical Materials

Purdue is a key partner in Critical Materials Institute
Critical Material Opportunities

**NdFeB Magnets – Nd, Dy**

**EOL Hierarchy:**
- Reuse whatever you can
- Remanufacture systems
- Remanufacture components
- Recycling
Need to consider economics and environment

**Advanced Batteries – Li, Co**

Need remanufacturing/recycling techs for critical material

Figure 6. In-use stock and demand neodymium [global, NdFeB magnets only].

Chart 1.1  Next-Generation Advanced Battery Energy Capacity and Revenue by Region, All Applications, World Markets: 2014-2023

(Source: Navigant Research)
Techno-Economic Analysis (TEA)

♦ Working with DOE scientists to advance their technologies
  • Economic feasibility opportunities
  • Improvement opportunities
  • Bottlenecks

♦ One example: extracting high-value REEs from waste streams (recycling) with biosorption

Step 1: Bioengineer microbes
Step 2: Rare earth biosorption
Step 3: Rare earth recovery

https://www.netl.doe.gov/sites/default/files/netlfile/20180410_1130C_Presentation_TCF-17-13365_LLNL.pdf
TEA Results

♦ TEA of Biosorption (Waste Feedstock Comparison)

<table>
<thead>
<tr>
<th>Feedstock Type</th>
<th>Coal ash**</th>
<th>Mine tailings</th>
<th>Round Top</th>
<th>Bull Hill</th>
<th>Ion exchange clay</th>
<th>Geothermal brine</th>
</tr>
</thead>
<tbody>
<tr>
<td>REE content (ppm)</td>
<td>337-603</td>
<td>178-232</td>
<td>633</td>
<td>2,800</td>
<td>131-293</td>
<td>0.6-3.2</td>
</tr>
<tr>
<td>Unit production cost ($/kg TREO)</td>
<td>147-249</td>
<td>353-456</td>
<td>145</td>
<td>25</td>
<td>275-590</td>
<td>132-582</td>
</tr>
<tr>
<td>Current TREO basket price ($/kg TREO)*</td>
<td>306-368</td>
<td>13-14</td>
<td>28</td>
<td>13</td>
<td>13</td>
<td>17-22</td>
</tr>
<tr>
<td>TREO price increase required for break-even (x-times)</td>
<td>0.5-0.7</td>
<td>27-34</td>
<td>5</td>
<td>2</td>
<td>22-46</td>
<td>8-27</td>
</tr>
<tr>
<td>Capital cost (in $ million) assumed life of 20 years</td>
<td>5.6-6.2</td>
<td>5.2-5.4</td>
<td>11.0</td>
<td>53.5</td>
<td>6.0-6.8</td>
<td>60.7-61.1</td>
</tr>
</tbody>
</table>

*We discounted our TREO price (at 95% or higher purity) by 30% from the 99+% pure individual REO prices.

**Coal ash: 94-95% of the revenue is from scandium.

♦ TEA of Biosorption (Costs)

<table>
<thead>
<tr>
<th>Processing Steps</th>
<th>Cost %</th>
</tr>
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<tbody>
<tr>
<td>Pre-processing (including leaching)</td>
<td>80.7%</td>
</tr>
<tr>
<td>Biosorption</td>
<td>16%</td>
</tr>
<tr>
<td>Oxalic precipitation &amp; Roasting</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

Industrial Symbiosis: Reuse Wastes

♦ **Industrial Symbiosis**
  - Synergistic exchanges
  - Material, water, byproducts → treating “waste” as feedstock
  - Minimize waste and reduce dependence on virgin resources

♦ **Life Cycle Symbiosis**
  - Use End-of-Life products to realize symbiotic opportunities

♦ **Example:** Use degraded EV battery for energy storage
  - Avoid impacts associated with new battery creation/old battery disposal
One Final Issue: Product Design

Most of the cost of a product is committed early in the design process (Thompson, 1997)

Product environmental impact is also committed early during design
Concept Design: Function-Impact Method

**Product A**

**Product B**

**Product C**

**New Product**

Dismantling → Value Recovery

Optimize Product Architecture to Facilitate Dismantling

Cost associated with each task

Whole Product

Completely Disassembled Product

Revenue gained by reaching different nodes

Network model of dismantling states

Employ Automation to Reduce Labor Costs

Automated disassembly line

## Metal Recycling Compatibility Guidelines

<table>
<thead>
<tr>
<th>Material Compatibility</th>
<th>Al (cast)</th>
<th>Al (wrt)</th>
<th>Cu alloys</th>
<th>Pb alloys</th>
<th>Mg Alloys</th>
<th>Pt-fam alloys</th>
<th>SS</th>
<th>Steel + Cast Fe</th>
<th>Zn alloys</th>
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<tbody>
<tr>
<td>Aluminum (cast)</td>
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<td>Copper alloys</td>
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<td>Pt-family alloys</td>
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<td>Steel + Cast Iron</td>
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- **Must separate**
- **Should separate**
- **Don't separate**

Summary

♦ Traditional product life cycle
♦ Product life extension
♦ Implementing reuse, remanufacturing, and recycling strategy
  • Techno-economic analysis
  • Industrial symbiosis
♦ Design – environmental engineers need to weigh in on this

Thank You for Your Attention!!
Questions??

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Circular Economy

♦ Circular Economy: An alternative to the traditional (make-use-dispose) linear economy.
  • Design out waste and pollution
  • Keep products and materials in use
  • Regenerate natural system

♦ Close Material Loops:
  • Extend product life
  • Extract maximum value
  • Recover, regenerate, and reintroduce

♦ Our tasks:
  • Implementing reuse/remanufacturing/recycling strategy
  • Techno-economic analysis (TEA)
  • Industrial symbiosis
Avoid
Reduce
Reuse
Remanufacture
Recycle
Recover Energy
Dispose
Used engine

Disassembly & cleaning

Inspection

Make up cores

Assemble

Remanufactured engine

Damaged parts

Recycle
Critical Materials Institute (CMI)

Assure supply of critical materials (rare earth elements) – needed for clean energy tech

• Enabling innovation in manufacturing
• Enhancing energy security.
Recovery – Rare Earth Elements (REE)

♦ U.S. in-use stock of REE magnets estimated at ~$5 billion (material value) – less than 1% currently recovered.

♦ Value likely underestimated:
  • Recycling may also recover other elements (e.g., Fe and Ni)
  • Remanufacturing could recover functional value
Recovery – Rare Earth Elements (REE)

♦ Provides another option to using virgin resources (China has > 85% of REE resources)

♦ Recycling REE could lower cost of materials, maximize the use of REE, and meet the increasing needs of REE.

[Graph showing Rare Earth Element Production from 1994 to 2017]
Recovery – Wind Turbines

- Reuse composite materials as primary strategy
- Remanufacture units and relocate them in medium scale applications.
- Remanufacture of subsystem to supply spare parts.
- Recycling of critical materials (e.g., REEs)
Enable Usage of Low-grade REE Sources for Downstream REE purification

- solid REE feedstock → communion → chemical leachate or solution feedstock
- total rare earth oxides ← oxalic precipitation & roasting ← Biosorption: enrich and concentrate REEs

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